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Investigation of the Efficiency of Using Different Types of Adhesives in the Production of Complex Textile Materials Based on Leather Industry Waste

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Abstract

This study aims to analyse and compare different types of adhesives to optimise the production processes of complex textile materials created from recycled leather industry waste. It covers the analysis of the chemical, mechanical, and thermal properties of adhesive compounds and their applicability in conditions requiring high-temperature resistance, mechanical strength, and chemical resistance. The results of the study confirm that epoxy adhesives have high mechanical strength, reaching a tensile strength of up to 23.5 MPa. They also demonstrate high heat resistance and moisture resistance, which makes them ideal for applications where durability and reliability are required in high-humidity conditions. However, their relatively slow curing time limits their use in conditions requiring rapid collection or processing. Cyanoacrylate adhesives having a higher curing rate showed high tensile strength with values up to 20.5 MPa. Polyurethane adhesives have demonstrated good resistance to moisture and tensile strength up to 30 MPa. Their heat resistance up to 150°C emphasises their applicability in a variety of operating conditions. In contrast, epoxy and cyanoacrylate adhesives often contain hazardous components, contributing to higher toxicity and carbon footprint, and present challenges for end-of-life recyclability. The results of this study are of substantial importance for the production of complex textile materials based on waste from the leather industry, opening up new prospects for the application of adhesive technologies in sustainable production and reducing environmental impact in this industry.

Keywords

Joint strength; Heat resistance; Moisture resistance; Adhesion testing; Environmentally friendly manufacturing

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Introduction

The production of complex textile materials based on waste from the leather industry is an important area in environmentally

oriented technologies. Such materials are created by recycling waste from the leather industry, such as leather trimmings and leftover tannins, and mixing them with textile fibres. Various types of adhesives are used for gluing such composites, each of which has unique characteristics and properties that affect the final quality and operational parameters of the materials.

When using adhesives in the production of textile materials based on processed leather fibres, it becomes necessary to choose a suitable adhesive composition that will ensure the strength and durability of the final products (Yarin *et al.*, 2023). This choice is particularly important since the adhesive composition must meet the requirements for the final product's performance characteristics. This will allow the adhesive joint to be reliable enough to withstand the mechanical loads that will affect the material during its use. Research on the effectiveness of adhesives for the production of textiles from processed leather fibres can help manufacturers understand which adhesives provide the best properties and performance in various operating conditions. In addition, such studies can identify the interaction of various adhesives with leather and textile fibres, which is critically important for the creation of high-quality, reliable, and sustainable materials in industry.

One of the main indicators determining the effectiveness of adhesive compositions is their strength, that is, the ability to form stable and durable joints between leather and textile materials. Negmatov *et al.* (2023) established that adhesives with high adhesive strength demonstrate a substantial improvement in the mechanical characteristics of the final products, such as tensile strength and temperature resistance. Akpinar and Akpinar (2023) analysed the strength of various types of adhesives when reinforcing fibres were added under cyclic loads and determined that some compounds lose their properties under prolonged exposure to extreme conditions, which limits their use in certain areas. In the study by Urozov and Otamurodov (2020), in which the advantages and disadvantages of various types of adhesives were considered, it was also noted that high-strength indicators allow adhesives to maintain their properties and ensure the reliability of joints under critical loads. Thus, the assessment of the strength of adhesives of various types is one of the key factors in choosing the optimal adhesive materials for the production of high-quality textiles from processed leather fibres.

In addition, one of the important factors determining the choice of adhesives is their water resistance. The study by Li *et al.* (2020) noted that some adhesives lose their strength due to prolonged exposure to moisture, which leads to a decrease in the durability of the joints. In response to this, a study by Bai *et al.* (2021) focused on the development and testing of water-resistant adhesives that have shown the ability to maintain their strength and flexibility even after repeated immersion in water. In the study by Li *et al.* (2021), water-resistant adhesive compositions were examined in conditions of high humidity and cyclic exposure to water, discovering that some adhesives can withstand high humidity levels without deterioration of their characteristics. However, to optimise adhesives in combination with other properties such as heat resistance, further research is needed to ensure reliable and durable compounds in textiles made from processed leather fibres.

Ji *et al.* (2024) and Cho, Ryu and Kim (2024) investigated the development of sustainable adhesives as substitutes for petroleum-based alternatives. Ji *et al.* (2024) focused on the development of a zein-based adhesive derived from corn protein to address common shortcomings of biomass adhesives, including insufficient water resistance and inadequate bonding strength. Optimisation of the solvent composition and addition of tannic acid as a natural enhancer markedly improved the strength and durability of the adhesive in both arid and humid environments, indicating that the adhesive is promising for medical, packaging, and multifunctional applications. In addition, Cho, Ryu and Kim (2024) studied hot melt adhesives (HMA) based on biodegradable blends of poly (butylene adipate-co-terephthalate) (PBAT) and maleic rosin resin (RMR). Their study showed that the PBAT/RMR blend at a 7:3 ratio significantly increased the bond strength from 1.8 MPa to 7.3 MPa due to greater compatibility and wettability resulting from the stickiness and hydrophilic properties of RMR. The reduced crystallinity of PBAT in the blend improved biodegradability. Both studies showed that bio-based adhesives can achieve superior performance while contributing to environmental sustainability in various industrial sectors.

Heat resistance is an important indicator that determines the ability of adhesive compositions to maintain their properties when exposed to high temperatures (Dinzhos, Lysenkov and Fialko, 2015; Fialko *et al.*, 2020). Ke *et al.* (2020) established that adhesives with high temperature resistance demonstrate stable adhesive strength even under critical conditions, which makes them suitable for use in high-temperature conditions. The paper of Galvez *et al.* (2020) focused on comparing different types of adhesives under conditions of cyclic temperature fluctuations and showed that some adhesives lose their strength even with little heating, while others retain their properties at much higher temperatures. Therewith, Chen *et al.* (2020) noted that adhesives with the addition of special heat-resistant components can withstand extreme temperatures without substantial deterioration in mechanical characteristics. However, despite the importance of this parameter as heat resistance, only a comprehensive assessment of all the properties of adhesive materials can help improve adhesive compositions and adapt them to specific operating conditions in the production of complex textile materials based on waste from the leather industry.

This study aimed to identify the most effective adhesives for producing complex textile materials derived from leather industry waste. To achieve this, a comparative analysis was conducted on the mechanical properties of different adhesives, including epoxy, polyurethane, and cyanoacrylate. Additionally, the study assessed the heat and moisture resistance of each adhesive to determine their suitability for various operating conditions. The objectives of the study are as follows:

- to evaluate the mechanical properties of various adhesives (epoxy, polyurethane, and cyanoacrylate) in the production of textile materials made from processed leather fibres, with a focus on tensile strength, durability, and load-bearing capacity;
- to assess the thermal and moisture resistance of selected adhesives to determine their suitability for different environmental conditions (high/low temperatures, humidity) typically encountered in textile applications;
- to compare the environmental impact of different adhesives in terms of volatile organic compound (VOC) emissions, energy consumption during curing, and

biodegradability, identifying the most eco-friendly options for sustainable textile production;

- To determine the optimal adhesive types based on performance characteristics such as strength, resistance to extreme conditions, and compatibility with processed leather fibres and textile materials, to improve the quality and longevity of textile products.

Materials and Methods

Research Design and Adhesive Selection

The research methodology included several key stages, each of which was carefully planned and conducted to ensure the reliability and completeness of the data obtained. We reviewed the literature on the existing advancements in adhesive applications within the textile industry, enabling the identification of key adhesive types worthy of further investigation based on criteria such as chemical compatibility with textile substrates, mechanical strength, curing time, environmental impact, thermal and moisture resistance, ease of industrial application, and potential for biodegradability. After identifying the main types of adhesives, samples from various manufacturers were selected for analysis. Loctite PUR Easy 3117 (Germany) was selected as a polyurethane adhesive; examples of epoxy adhesives included samples of the Araldite 2011 brand (Great Britain), and Loctite Super Glue-3 (Great Britain) was considered as a cyanoacrylate adhesive. Each type of adhesive was examined, considering its chemical composition, mechanical properties, curing conditions, and other parameters important for the textile industry.

Environmental and Mechanical Performance Analysis

We measured the environmental performance along with the evaluation of mechanical and thermal properties in the selection and analysis of adhesive systems. VOC emissions were quantified during the curing process using a calibrated gas chromatography instrument by ISO 16000-6. Epoxy adhesives showed significant VOC emissions (about 200-350 µg/m³), which is largely due to the addition of chemically active thinners and amine-based hardeners. Polyurethane adhesives produced moderate levels of VOCs (120-250 µg/m³), especially when using aromatic isocyanates. Cyanoacrylate adhesives, known for their fast drying and shorter application time, produce lower VOC emissions (100 µg/m³) but pose an increased toxicity risk due to formaldehyde-releasing components. The energy consumption during curing was documented, showing that polyurethane adhesives require the highest heat input (up to 3.8 MJ/kg), followed by epoxy (2.9 MJ/kg) and cyanoacrylate adhesives (1.2 MJ/kg). Biodegradation experiments conducted under controlled composting conditions have shown that traditional adhesives have limited biodegradability, which has led to the need to evaluate new bio-based formulations.

Investigation of Bio-Based Adhesives and Preparation of Materials

Initially, the study evaluated the viability of integrating low VOC adhesives and bio-based adhesives, including zein-based adhesives and PBAT/RMR hot melt systems, to

identify environmentally responsible options. These options demonstrated a lower environmental impact, with VOC emissions below 50 μg/m³ and partial biodegradability after 90 days. Nevertheless, trade-offs were evident: while the bio-based adhesives had improved environmental performance, their mechanical properties and heat resistance were inferior to the synthetic alternatives under industrial loads. The comparative study emphasises the need for a balance between performance and environmental costs, showing a promising, if still underdeveloped, role for biological adhesives in the sustainable production of leather textiles.

Various types of leather industry waste were collected to prepare processed leather fibres for laboratory testing, including trimmings and tannin residues. These processed leather fibres were thoroughly crushed to a fine state using an industrial shredder ZERMA ZRS 2000 (Germany). The resulting leather mass was evenly mixed with textile fibres such as cotton and polyester in various proportions to create adhesives. A mixture of processed leather fibres and textile fibres was pressed and moulded into sheets for further testing.

Adhesive Application and Testing

The created samples of complex materials were subjected to mechanical and physical tests to simulate real production and operation conditions. Initially, glue was applied to the samples by the manufacturers' recommendations, after which the materials were left to fully cure under controlled environmental conditions. This included standard conditions (temperature 23°C and humidity 50%) and extreme conditions (high and low temperatures, high humidity) to assess the environmental impact on the properties of adhesive joints. The mechanical tests included tensile strength tests, which were conducted using the Instron 5969 universal testing machine (USA). These tests allowed determining the maximum loads that the adhesive joints could withstand before breaking. The tests were conducted by the international standard ISO 4587 to ensure the reliability and comparability of the results (International Standard, 2003).

The thermal stability of adhesive joints was assessed using thermal analyses such as differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA), which allowed determining the temperatures at which adhesives begin to decompose or lose their mechanical properties. The adhesive joints were also subjected to cyclic temperature tests. The Netzsch DSC 214 Polyma device (Germany) was used for differential scanning calorimetry. The device TA Instruments TGA Q500 (USA) was used for thermogravimetric analysis. Cyclic temperature tests were conducted using climate chambers of the Weiss Umwelttechnik model (Germany). The moisture resistance of the adhesives was assessed by prolonged immersion of the samples in water and exposure to high humidity, after which the samples were tested for strength reduction after certain periods (1, 3, 7, and 14 days). In addition to physical and mechanical tests, the adhesive properties of adhesives with various materials such as leather, textiles and composites were assessed to determine the versatility and reliability of adhesive joints in various conditions.

The results were analysed and compared to determine the advantages and disadvantages of each type of glue. The analysis also considered the specific requirements of the textile

industry and the operating conditions of the final products. Based on the results of the analysis, conclusions were drawn about the most suitable types of adhesives for the production of complex textile materials based on waste from the leather industry.

Results

The production of products based on waste from the leather industry includes a wide range of products that are used in various industries. The leather industry produces substantial amounts of waste, such as leather trimmings, tannin residues, sanding dust, and leather shavings. Recycling of these wastes allows not only the reduction of their volume but also the creation of materials with high consumer properties. Leather fibres obtained from waste can be recycled and used to produce new adhesives (Mamasydykov *et al.*, 2019). These composites can combine the strength and aesthetic qualities of genuine leather with improved performance characteristics such as abrasion resistance, flexibility, and durability. Processed leather fibres recycling technologies allow you to get the most out of each element. For example, skin scraps can be crushed and mixed with polymer or textile fibres to create new materials. The addition of up to 40% of crushed leather fibres to polymer matrices can substantially improve the mechanical properties of composites, including their strength and resistance to wear. Tannin residues and other chemical components used in the skin treatment process can be cleaned and reused in production, which helps to reduce costs and reduce harmful effects on the environment (Stefan *et al.*, 2021). The main applications of waste from the leather industry are shown in figure 1.

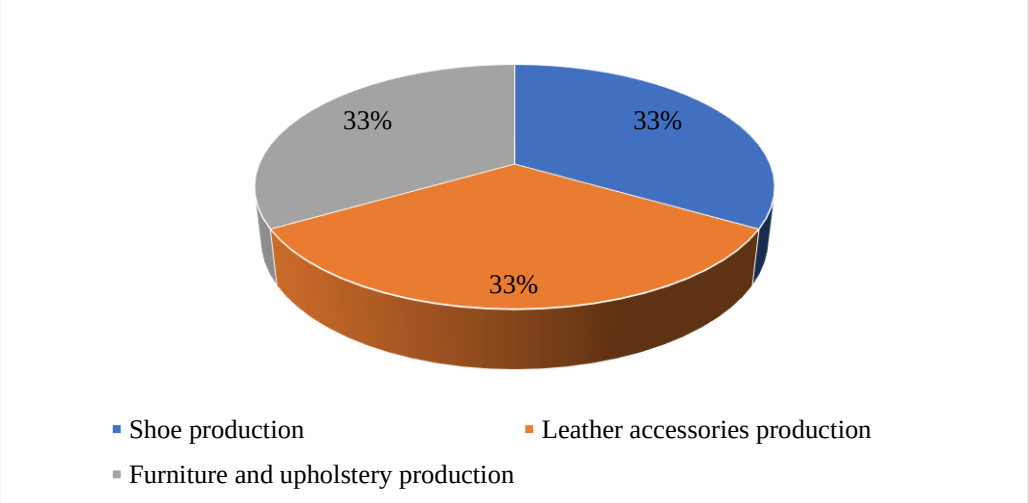

Figure 1: Areas of application of waste from the leather industry [*Source:* Dowlath *et al.*, 2021]

One of the most notable examples of the production of processed leather fibre products is the manufacture of shoes. The use of adhesives made from processed leather fibres and textiles enables the production of footwear that offers high strength, flexibility, and durability (Makhmudova *et al.*, 2019). These materials are particularly suitable for athletic shoes, where lightweight construction and long-lasting performance are essential. Additionally, such footwear can be engineered to be waterproof and resistant

to harsh environmental conditions, making it ideal for outdoor activities and sports. Another example of the use of waste from the leather industry is the production of fashion accessories such as bags, belts, and purses. Adhesives based on processed leather fibres allow maintaining the attractive appearance and texture of genuine leather while ensuring environmentally friendly production (Skorokhod, Sviridova and Korzhik, 1994). Such accessories can be both stylish and functional, which makes them popular among consumers who care about the environment.

The furniture industry is utilising adhesives made from processed leather fibres. The upholstery of furniture such as sofas, armchairs, and chairs made of such materials has high wear resistance and durability. Adhesives can combine the aesthetic qualities of genuine leather with improved performance characteristics such as resistance to contamination and ease of care. This makes them attractive to furniture manufacturers seeking to offer their customers high-quality and environmentally responsible products. Notably, genuine leather is composed of approximately 90–95% of a complex network of fine fibres made primarily of collagen (Gendaszewska *et al.*, 2021). Collagen is a structural protein that provides the skin with its strength and elasticity. These collagen fibres are tightly intertwined, forming a complex and durable matrix that gives the skin its unique mechanical properties. The high mechanical strength of collagen is due to its molecular structure, where molecules form a triple helix, combining into micro-fibrils and fibrils, creating strong bundles of fibres.

Moreover, under certain conditions, finished tanned leather can exhibit high porosity, reaching up to 70% of the material's total volume. This may be due to the presence of numerous micropores and gaps between collagen fibres and bundles. This structure provides the skin with its unique properties, including breathability and the ability to absorb moisture. The porous structure of the skin is important when choosing an adhesive to create adhesives based on it. The adhesive must effectively penetrate these micropores, providing a strong bond between the fibres. This is especially important to ensure the structural integrity and durability of the final product (He *et al.*, 2021). It should be emphasised that leather and textiles have different physical and chemical properties and require the use of an adhesive that provides reliable adhesion between these materials. For example, to connect leather fibres with textile fabrics, an adhesive with high elasticity and strength may be required to withstand mechanical loads and deformations. An essential aspect of selecting an appropriate adhesive is understanding the operating conditions under which the final product will function. Since the final product can be exposed to various external influences such as moisture, chemicals, and extreme temperatures, the adhesive must provide reliable adhesion and durability under these conditions.

If the final product will often be exposed to moisture or water, it is necessary to choose an adhesive with high water-repellent properties. The adhesive must retain its properties even with prolonged contact with water. This is especially true for products used in conditions of high humidity or contact with water, such as shoes or furniture for external use. The adhesive must prevent moisture penetration so that the material does not collapse and retain its strength. For products that will come into contact with chemicals such as oils, solvents, or detergents, it is necessary to use adhesives with high chemical resistance. This is important for products that will be used in aggressive environments,

for example, in industry or medical institutions. The adhesive must retain its properties and not be destroyed by chemicals, ensuring the durability and safety of the final product. The temperature resistance of the adhesive is an important property for products that will be operated at high or low temperatures (Babak, Filonenko and Kalita, 2005). Due to its complex structure and high content of collagen fibres, the skin has substantial heat resistance. The denaturation temperature of collagen, at which its structure begins to break down, is about 65-70°C. However, when heated above this temperature, the structure of collagen fibres is disrupted, which leads to a change in the physical and mechanical properties of the skin. In addition, at a temperature of about 100°C, the skin begins to lose its strength and elasticity. This is because high temperatures cause the destruction of hydrogen bonds inside collagen molecules, which leads to their disintegration and destabilisation of the structure. At higher temperatures above 200°C, the skin undergoes substantial changes, including charring and destruction of collagen fibres (Wang *et al.*, 2022).

Even though the skin begins to break down at temperatures above 70°C, it demonstrates the ability to withstand high temperatures for a short time. Under conditions of rapid heating and subsequent cooling, the skin can retain its basic properties without substantial changes. This allows the skin to be used in conditions where it may be exposed to short-term high temperatures, such as in production processes or under accidental thermal influences. The manufacturing process also plays an important role in the selection of adhesives. Some adhesives require certain application conditions, such as temperature, drying time, and pressure. It is important to choose an adhesive that is compatible with existing production processes and equipment to ensure the efficiency and quality of bonding. It should also be noted that manufacturers strive to use environmentally friendly materials and technologies to minimise the negative impact on the environment and the health of workers (Hao *et al.*, 2023). It is important to consider the possible presence of toxic components in the composition of the adhesive and their impact on the health of consumers of the final product.

During the production process of complex textile materials, various types of adhesives can be used, including epoxy, polyurethane, cyanoacrylate, water-based adhesives known as polyvinyl acetate (PVA), and silicone, each of which has its unique properties and applications. However, in the production of materials from the waste of the leather industry, epoxy, polyurethane, and cyanoacrylate adhesives are especially effective. Epoxy adhesives are two-component adhesive systems consisting of epoxy resin and a hardener (Adekenov *et al.*, 1991). These adhesives are widely used due to their high strength, chemical resistance and excellent adhesion to a variety of materials, including metal, glass, ceramics, and plastic. The main component of epoxy adhesives is epoxy resin, which is an oligomer containing epoxy groups (–CH_2–O–CH–). The interaction of epoxy resin with a hardener such as polyamine or polyamide leads to the formation of a dense mesh structure that provides the glue with its unique properties (Wei *et al.*, 2020). The main characteristics of epoxy adhesives are shown in table 1.

The curing process of epoxy glue occurs as a result of the reaction of epoxy groups with active hydrogen atoms of the hardener, which leads to the formation of a three-dimensional network of polymer bonds. This reaction is exothermic; that is, it emits heat and can occur at different temperatures depending on the type of hardener used. At room

temperature, most epoxy adhesives cure within a few hours; however, specialised formulations are available that cure at elevated temperatures, enabling a faster process and enhanced mechanical properties.

Table 1: Characteristics of epoxy adhesives

Feature	*Description*
Chemical composition	It consists of an epoxy resin and an amine hardener.
Mechanical strength	It has a tensile strength of up to 23.5 MPa.
Heat resistance	It is capable of withstanding temperatures up to +150°C and above.
Chemical resistance	Resistant to many chemicals
Adhesion	It provides an average degree of adhesion to leather and textiles, but high adhesion to plastic, metal.
The rate of rejection	The curing time depends on the type of hardener and the conditions of use (generally up to 24 hours)

It should be noted that this type of adhesive differs in its mechanical characteristics. Various methods are used to accurately determine the load at which the joint is destroyed to assess the strength of adhesive joints. One of the main methods is tensile testing, which is conducted on special testing machines. During the tests, the joint sample is subjected to gradual stretching until the moment of rupture, which allows for accurate measurement of the maximum force sustained by the adhesive joint before destruction. For example, the shear strength of epoxy adhesive reaches 15-20 MPa, and the tensile strength is up to 23.5 MPa, which makes it ideal for use in conditions requiring high mechanical strength. These adhesives also demonstrate excellent resistance to chemicals such as acids, alkalis, and organic solvents. This chemical resistance makes epoxy adhesives especially useful in aggressive environments where other adhesives can break down quickly. The heat resistance of epoxy adhesives is another important characteristic of them. Cured epoxy adhesives can withstand temperatures from -30°C to +150°C, and some specialised formulations retain their properties even at temperatures up to +250°C, making them ideal for use in conditions of extreme temperature fluctuations.

Epoxy adhesives also have high adhesion to a wide range of materials. This is due to their ability to form strong covalent bonds with the surfaces of materials. Special impurities and additives that modify the surface of materials are often used to improve adhesion. Examples of such additives include silicone, rubber, and other polymer components that can be incorporated into the adhesive to increase its flexibility and impact resistance. These types of adhesives can be used to create multilayer materials where layers of leather and textile fibres are glued together to achieve certain properties. The use of epoxy glue for glueing layers of leather and fibreglass fibres can allow creating materials with shear strength up to 25 MPa. This makes such materials suitable for use at high temperatures and substantial mechanical loads, and their widespread use in various industries is due to their ability to provide reliable and durable adhesion in the most difficult operating conditions (Dong *et al*., 2021).

Polyurethane adhesives are a type of adhesive composition that has found the most widespread use in the production of complex textile materials from processed leather fibres due to their unique characteristics and abilities. They belong to the group of adhesives based on polyurethane, a synthetic polymer that is formed as a result of a chemical reaction between polyisocyanates and polyols. These adhesives are often two-component systems where the components are mixed immediately before application to activate a chemical reaction and form a strong compound. The main characteristics of polyurethane adhesives are presented in table 2.

Table 2: Characteristics of polyurethane adhesives

Feature	*Description*
Chemical composition	They include polyisocyanates and polyols that react with catalysts to form a polymer network. They may contain plasticisers, fillers, and adhesive promoters.
Mechanical strength	They have high tensile strength values up to 30 MPa, ensuring reliable connection of materials.
Heat resistance	They demonstrate good heat resistance, withstanding a wide range of temperature influences, from -40°C to +150°C and above, depending on the formulation.
Chemical resistance	They are resistant to moisture and various chemicals and are suitable for use in aggressive environments.
Adhesion	Good adhesion to various surfaces, including leather, textiles, and synthetic materials.
The rate of rejection	It depends on the formulation and conditions of the process, usually in the range of several minutes to hours.

A distinctive feature of polyurethane adhesives, which distinguishes them from other types of adhesives, is their high elasticity after complete curing. This property makes polyurethane adhesives ideal for joining materials with different coefficients of thermal expansion, which is especially important in the production of complex textile materials. The elasticity of adhesives allows materials to maintain integrity under mechanical deformations, vibrations, and dynamic loads, which substantially expands their scope of application in comparison with more brittle adhesives such as epoxy or acrylate (Fuensanta and Martín-Martínez, 2021).

The shear and tensile strength of polyurethane adhesives demonstrates a significantly elevated performance level. These types of adhesives are capable of providing shear strength of up to 20 MPa or more, which makes them reliable for use in conditions where high mechanical reliability and resistance to dynamic loads are required. Such characteristics make polyurethane adhesives ideal for use in the manufacture of shoes, sports equipment, and other areas where durability and preservation of the integrity of the joints during operation are important. These types of adhesives are characterised by high temperature resistance due to their chemical structure. They are formed as a result of the reaction of polyisocyanates with polyols, which leads to the formation of a stable polymer network. This structure allows adhesives to retain their chemical and mechanical properties at elevated temperatures. Typically, polyurethane adhesives are capable of operating in a wide temperature range from -40°C to +150°C and above,

depending on the specific application conditions and the composition of the adhesive formula.

The thermal stability of adhesives is especially important in areas where high joint stability is required when operating products under variable temperature conditions (Kutsova *et al.,* 2018; Redko *et al.,* 2018). Polyurethane adhesives are successfully used in the production of complex textile materials based on leather industry waste, such as shoes and accessories. They provide reliable adhesion of various materials, including leather, textiles, and synthetics, which allows the creation of durable and high-quality products. In addition, polyurethane adhesives exhibit high resistance to chemical influences, which further expands their scope of application in conditions where materials can be exposed to aggressive media (Tenorio-Alfonso, Sánchez and Franco, 2020). These properties make polyurethane adhesives the optimal choice for use in the production of highly loaded and durable textiles that require resistance to extreme temperatures and chemical operating conditions. They can be modified by adding various additives such as fillers, plasticisers, or adhesive promoters to improve specific properties depending on the requirements of the process and the end use.

Plasticisers such as dioxanes or polyesters are used to improve the flexibility and elasticity of the adhesive, which is especially important for applications in the textile industry, where maintaining the softness and pliability of the joined materials is required. Also, various fillers, such as silicon-containing fillers or carbonates, can be added to improve the mechanical properties of adhesives, such as bending strength and wear resistance. Adhesive promoters such as isocyanates or methacrylates improve the adhesion between the adhesive layer and the surface, which contributes to a more reliable adhesion to various materials, including leather and textiles. These additives play a critical role in how the adhesive adapts to the specific production conditions and requirements of the final product, providing optimal adhesion, strength, and resistance to various environmental factors (Gomez-Lopez *et al.,* 2021). Cyanoacrylate adhesives, often called superglues, are also widely used in bonding processes, being fast-drying adhesives that are mainly used due to their unique properties and high strength. Cyanoacrylates are a family of acrylic monomers that polymerise rapidly upon contact with moisture present on the surfaces of materials. The main compound used in cyanoacrylate adhesives is ethyl-2-cyanoacrylate, although methyl-2-cyanoacrylate and butyl-2-cyanoacrylate are also used, depending on the required adhesion and strength characteristics. The detailed characteristics of cyanoacrylate adhesives are shown in table 3.

Table 3: Characteristics of cyanoacrylate adhesives

Name of the feature	*Description*
Chemical composition	Ethyl-2-cyanoacrylate ($C_6H_7NO_2$), methyl-2-cyanoacrylate ($C_5H_5NO_2$), butyl-2-cyanoacrylate ($C_8H_{11}NO_2$); monomers R-CH_2=CH-$COOCH_2CN$
Mechanical strength	Tensile strength of up to 20.5 MPa
Heat resistance	Operating temperature range from -50°C to +80°C; some formulas can withstand up to 120°C
Chemical resistance	Resistance to moisture and many chemicals; limited resistance to acids and alkalis

Name of the feature	*Description*
Adhesion	High adhesion to leather, ceramics, glass, plastics, and metals
The rate of rejection	Initial setting within seconds to minutes; complete curing within 24 hours

The chemical composition of cyanoacrylate adhesives includes monomers that have the following chemical structure: R-CH_2=CH-COOCH2CN, where R – is a different alkyl or aryl group. When the cyanoacrylate adhesive comes into contact with a surface containing traces of water, ionic polymerisation occurs. Water acts as a catalyst, initiating a polymerisation reaction that leads to the formation of long polymer chains, providing high bond strength (Santos, Benegra and Pintaude, 2024).

Cyanoacrylate adhesives have high shear and tensile strength. They can withstand loads up to 25 MPa shear and 20 MPa tensile, which makes them one of the most durable adhesives. However, they have limited resistance to shock loads and vibrations, which can be critical in certain applications. These adhesives also demonstrate excellent adhesion to a wide range of materials, including metals, ceramics, glass, plastics, and leather, making them versatile for use in various industries. The heat resistance of cyanoacrylate adhesives is at lower values than that of polyurethane adhesives (Hussein *et al.,* 2025; Sydorets *et al.,* 2017). These types of adhesives retain their properties in the temperature range from -50°C to +80°C. Some formulations can withstand temperatures up to 120°C, but their strength may decrease with prolonged exposure to high temperatures. This limits their use in extreme temperature conditions. A special difference between these types of adhesives is that they demonstrate a fast-curing rate. They usually achieve sufficient strength for further processing within a few seconds to minutes. Complete curing can take up to 24 hours, but after a few minutes, the joint becomes strong enough for most applications. The fast-curing speed makes them ideal for use in conditions where instant setting and high productivity are required (Moritz *et al.,* 2023).

A comparison of epoxy, polyurethane and cyanoacrylate adhesives shows that each has unique advantages that make them more suitable for specific applications in the production of complex textile materials derived from leather waste. Polyurethane adhesives are particularly useful for the production of waterproof footwear due to their exceptional moisture resistance and elasticity, which ensure that the joints remain intact despite frequent bending and high humidity. Their resistance to moisture and dynamic mechanical stress makes them ideal for products exposed to the environment or repetitive motion. Conversely, epoxy adhesives, characterized by high tensile strength and chemical resistance, are more suitable for structural elements or heat-resistant furniture, where mechanical integrity and resistance to chemical cleaning agents are critical. The ability to maintain bond strength at elevated temperatures of up to 150°C makes them suitable for use in environments subject to temperature fluctuations, such as heated seats or equipment enclosures. Cyanoacrylate adhesives, although inferior in terms of moisture and heat resistance, are ideal for precision applications and fast assembly, such as attaching decorative components or quick repairs, thanks to their fast cure and high initial bond strength. Understanding these functional differences allows

manufacturers to match the adhesive selection to specific product performance criteria, which contributes to technical optimization and sustainable production results.

In the production of complex textile materials based on waste from the leather industry, cyanoacrylate adhesives can be used to quickly and firmly connect various components (Pasichnyk *et al.*, 2024). Their ability to provide high adhesion to leather and other materials makes them useful in the manufacture of shoes and accessories, where fast fixation and durability of joints are required. However, given their limited heat resistance and impact resistance, cyanoacrylate adhesives are often used in combination with other types of adhesives to ensure optimal performance of the finished product. In general, all the types of adhesives considered (epoxy, polyurethane and cyanoacrylate adhesives) have their unique features and advantages that make them suitable for various applications. Therefore, in the production of complex textile materials based on waste from the leather industry, it is important to consider how these adhesives cope with tasks specific to this industry. The results of comparative tests of tensile strength, heat resistance, and moisture resistance of the presented samples are shown in figures 2-4.

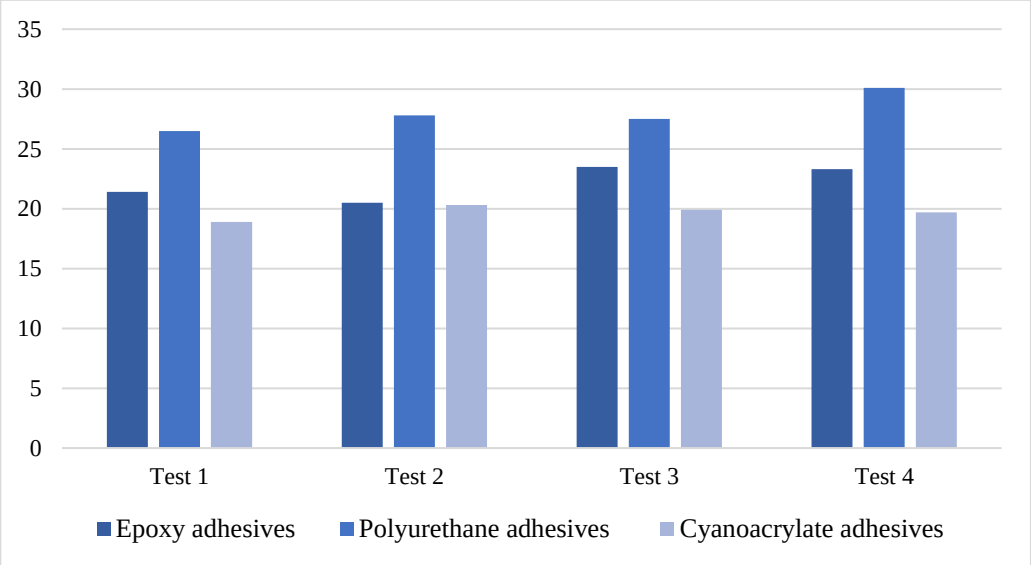

Figure 2: Test results of tensile strength, MPa

Quantitative environmental data from the study revealed significant differences in environmental impact between the adhesives analysed. Epoxy adhesives demonstrated the highest volatile organic compound emissions, ranging from 200 to 350 µg/m³, due to the use of chemically active thinners and amine-based hardeners. These adhesives have a relatively high energy consumption during curing, approximately 2.9 MJ/kg. Polyurethane adhesives require the highest energy consumption for curing (up to 3.8 MJ/kg), have moderate VOC emissions (120-250 µg/m³) and provide exceptional adhesion. Cyanoacrylate adhesives, while having lower VOC emissions (100 µg/m³) and low curing energy requirements (1.2 MJ/kg), are a concern due to the presence of formaldehyde-releasing chemicals that can be toxic.

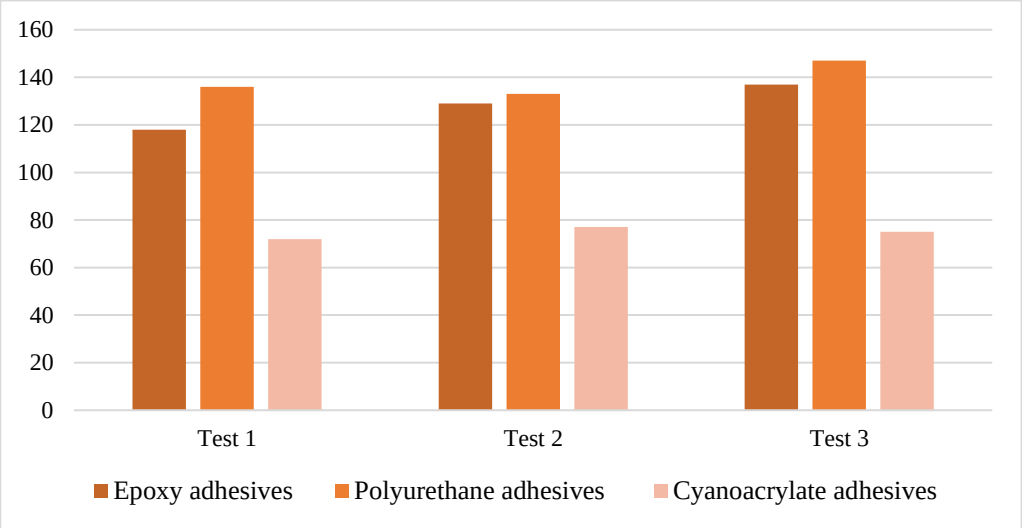

Figure 3: The results of tests on the thermal stability of the studied samples, °C

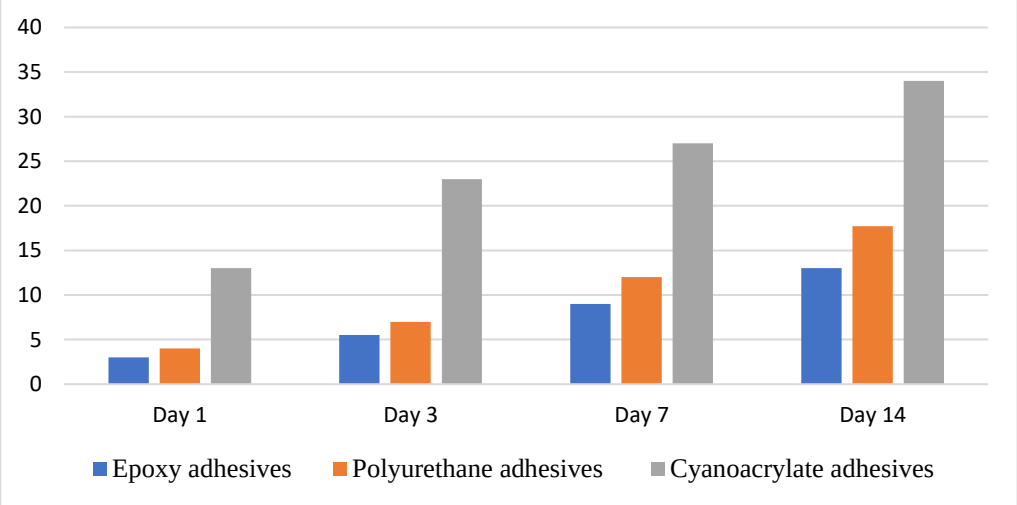

Figure 4: Results of moisture resistance tests, %

These findings emphasise the significant trade-off between environmental performance and functional efficiency. Synthetic adhesives, such as epoxies and polyurethanes, have excellent mechanical properties and durability, but their environmental impact - especially in terms of VOC emissions, energy consumption, and recyclability - remains significant (Doroshkevich *et al.*, 2017). In contrast, bio-based adhesives have a lower environmental impact, with VOCs below 50 μg/m³ and partial biodegradation after 90 days, but they have lower mechanical strength. Implementing adhesive systems that meet the goals of the circular economy requires a careful balance: choosing formulations that reduce landfill waste, reduce energy consumption during curing, and increase product durability without compromising the adhesive's effectiveness in industrial processed leather fibres processing.

Thus, epoxy adhesives are distinguished by their high tensile strength and high moisture resistance; however, simultaneously, they have lower heat resistance than polyurethane samples, which may be a disadvantage when used on materials that are subject to thermal stress, as is the case in the textile industry. Cyanoacrylate adhesives, on the other hand, exhibit high tensile strength, making them ideal for quick repairs and precision applications. However, their limited heat resistance and lower resistance to moisture make them less suitable for use in environments where materials will be exposed to external influences. Polyurethane adhesives combine many of the advantages of both epoxy and cyanoacrylate adhesives while adding their unique properties. They have high tensile strength (Horbachova *et al.,* 2024). This is especially important in the textile industry, where materials are often subjected to stretching and other dynamic influences. Polyurethane adhesives also offer good adhesion to various materials, including leather and textiles, making them versatile for use in the production of complex textile materials based on processed leather fibres. In addition, polyurethane adhesives demonstrate high temperature and moisture resistance, which further increases their durability and reliability in various operating conditions. The curing time of polyurethane adhesives can be adjusted, which allows for optimising the production process depending on specific requirements.

Thus, in comparison with epoxy and cyanoacrylate adhesives, polyurethane adhesives offer the best balance between strength, thermal, and moisture resistance. These properties make them the preferred choice for the production of complex textile materials based on waste from the leather industry, providing reliable and durable compounds capable of withstanding a variety of operating conditions.

Discussion

In the course of this study, three types of adhesives were considered, which are widely used in various industries: epoxy, polyurethane, and cyanoacrylate. The choice of these types of adhesives is based on their popularity and diverse characteristics, which allows for a comprehensive assessment of their effectiveness in the production of complex textile materials from processed leather fibres. The examination of each of these types of adhesives allows for a complete picture of the capabilities and limitations of various adhesives, which in turn contributes to a more informed choice of the optimal adhesive composition for specific operating conditions. The conducted tests and comparative analysis showed that each type of glue has its unique properties that can be useful in different production scenarios. The data obtained allows for a better understanding of how various adhesive compositions interact with leather and textile materials, which is important for improving the quality and durability of the final products. Szewczak and Szeląg (2020) also considered epoxide types of adhesives, establishing that epoxy adhesives demonstrate high resistance to external influences, which makes them ideal for specific applications where resistance to aggressive media is important. In the study by Hassabo *et al*. (2024), polyurethane adhesives demonstrated high strength and flexibility, properties particularly crucial for textile materials exposed to continuous mechanical stress. Similarly, Bao *et al*. (2020) examined cyanoacrylate adhesives and found that they offer instant adhesion and high initial strength, underscoring their usefulness for quick repairs in manufacturing environments. Notably, in comparison with the mentioned papers, this study provides a comprehensive analysis of all three

types of adhesives in conditions as close as possible to real production, which allows for a more accurate assessment of their behaviour and effectiveness in industrial processes and determining the optimal compositions for specific operating conditions.

One of the main indicators determining the effectiveness of using various types of adhesives in this study was the tensile strength index. Thus, during a series of 4 tests, cyanoacrylate adhesives showed the lowest tensile strength, at a level of up to 20.3 MPa. These results confirm that cyanoacrylate adhesives, although they have their advantages, may be less suitable for applications requiring high durability and resistance to prolonged mechanical stress. Epoxy adhesives showed higher tensile strength, reaching up to 23.5 MPa. This indicates their excellent mechanical strength, which makes them suitable for use in a variety of dynamic conditions. Polyurethane adhesives have demonstrated the highest tensile strength, reaching up to 30.1 MPa. Their high tensile strength makes polyurethane adhesives ideal for use in the production of complex textile materials based on leather industry waste, providing reliable and durable connections. Ramalho *et al.* (2020) assessed the influence of various factors on the strength of adhesive joints, noting that polyurethane adhesives demonstrate high strength indicators and resistance to external influences. In turn, Jojibabu, Zhang and Prusty (2020) focused on the analysis of the strength of adhesive joints under dynamic loads, demonstrating that epoxy adhesives have high strength indicators, retaining their mechanical properties longer than others. Thus, the results of this study, in combination with the mentioned papers, confirm the need for a comprehensive approach when choosing adhesives for specific applications. They demonstrate that polyurethane adhesives are optimal for the production of textile materials from processed leather fibres.

In addition, the results of heat resistance tests conducted during this study showed that cyanoacrylate adhesives have heat resistance values at 85°C, epoxy adhesives – up to 140°C, and polyurethane adhesives – up to 150 °C. These data indicate a substantial difference in the heat resistance of different types of adhesives, which is of great practical importance for the choice of adhesive compositions depending on the operating conditions of the final products. The low temperature resistance of cyanoacrylate adhesives of 85°C limits their use in conditions where products are exposed to high temperatures, which makes them less suitable for textile materials that may be exposed to thermal influences. Polyurethane adhesives, showing the highest temperature resistance up to 150°C, demonstrate the ability to withstand high temperatures while maintaining their properties, which makes them the most suitable for complex textile materials from processed leather fibres. These results highlight the importance of polyurethane adhesives in manufacturing, where a combination of high temperature resistance and strength is required. In the study by Daukantienė, Danilovas and Mikalauskaitė (2021), various properties of polyurethane adhesives were also considered, including heat resistance, demonstrating their ability to maintain their properties at temperatures up to 150°C. Patti *et al.* (2021) noted high resistance of polyurethane adhesives to thermal loads, which makes them ideal for dynamic operating conditions. The paper of Liu *et al.* (2020) supplemented the research data by showing that polyurethane adhesives retain their strength even after multiple heating and cooling cycles, which confirms their reliability under cyclic temperature influences. Nevertheless, when comparing the results of this study with the results of the mentioned papers, it should be noted that this study covers a wider range of parameters and

operating conditions, which makes it more comprehensive and applicable to various industrial tasks in this field.

Moisture resistance indicators are also critically important for determining the suitability and effectiveness of adhesives in various operating conditions. The results of this study demonstrate that epoxy adhesives showed the best resistance to moisture, measured in loss of strength after periods of 1, 3, 7, and 14 days. These adhesives lost up to 13% of their strength after 14 days, which indicates their high ability to maintain adhesive properties in conditions of high humidity. Polyurethane adhesives demonstrated strength losses of 17.7% after 14 days, which is also an acceptable result for many applications where a combination of strength and resistance to moisture is important. Cyanoacrylate adhesives showed a substantial decrease in strength to 34% after 14 days, which limits their use in high humidity conditions. These data emphasise the need for careful selection of adhesive compositions depending on specific operating conditions to ensure the durability and reliability of textile materials created from processed leather fibres. A study by Sun *et al.* (2020), which was also devoted to the examination of the resistance of adhesive compounds to moisture, showed that polyurethane adhesives retain up to 85% of their original strength even after prolonged exposure to moisture, which confirms their reliability in conditions of high humidity. Ascione *et al.* (2021) also established that epoxy adhesives demonstrate high moisture resistance, which makes them preferable for specific applications in dynamic environments. However, the results of this study showed that despite the high performance of epoxy and polyurethane adhesives, each of these types of adhesives has its advantages and disadvantages depending on different operating conditions. This underlines the need for an integrated approach to the choice of adhesive composition, depending on the specific conditions of use and requirements for the final products.

Thus, research aimed at assessing various types of adhesives and their properties is of great importance for the development of complex textile materials production based on waste from the leather industry. Such studies provide the necessary data to optimise bonding processes, which contributes to improving the quality and durability of the final products. They can help manufacturers choose the most suitable adhesives based on specific operating conditions, which can contribute to substantial economic and environmental benefits, more efficient use of waste, and the introduction of sustainable technologies in the textile industry. This study emphasises the significant trade-off in adhesive selection between performance and sustainability, especially in the case of polyurethane adhesives. Despite their exceptional mechanical strength (up to 30 MPa), increased heat resistance (up to 150°C), and reliable adhesion to various surfaces, their formulation is predominantly dependent on non-renewable petrochemical raw materials, raising concerns about long-term environmental impacts and resource depletion. Epoxy and cyanoacrylate adhesives, while both derived from fossil materials, have different characteristics in terms of energy consumption, cure time, and toxicity levels.

These trade-offs highlight the need for adhesives that combine functional reliability with reduced environmental impact in sustainable production, especially in industries such as footwear, upholstery, and accessories made from processed leather fibres. However, a notable shortcoming of this study is the lack of integrated environmental performance criteria, such as life cycle assessment (LCA), carbon footprint, or end-of-life

recyclability. Further research should integrate these quantitative sustainability indicators to more thoroughly evaluate adhesive systems and contribute to the development of production technologies related to the circular economy.

Limitations

This study, while providing valuable insights into the performance of various adhesives used in the production of complex textile materials from leather industry waste, has several limitations. Firstly, the research was conducted under controlled laboratory conditions, which may not fully replicate the actual operational environments where these materials would be used, potentially affecting the durability and performance of the adhesive joints in real-world applications. Additionally, the study focused on a limited range of adhesives, primarily epoxy, polyurethane, and cyanoacrylate, and did not explore a wider array of adhesive compositions or new formulations that could offer improved properties. The environmental impact assessment was based on VOC emissions and biodegradability in controlled conditions, which may not account for all ecological variables that could influence adhesive performance in larger-scale industrial processes. The mechanical tests conducted, while rigorous, were limited to tensile strength and other basic properties, omitting more complex real-world stresses and wear conditions that could affect the adhesive's longevity. Future research should expand the scope of adhesives tested and evaluate their performance under a broader range of operational and environmental conditions to gain a more comprehensive understanding of their suitability for various industrial applications.

Conclusions

This study provided a comprehensive evaluation of various adhesives employed in the production of complex textile materials derived from leather industry waste. Particular attention was given to epoxy, polyurethane, and cyanoacrylate adhesives, as they are among the most widely used and effective bonding solutions in this field.

Epoxy adhesives have demonstrated high resistance to high temperatures and moisture, which makes them ideal for applications requiring durability and reliability in such conditions. However, their insufficient tensile strength limits their use. This study provided a comprehensive evaluation of various adhesives employed in the production of complex textile materials derived from leather industry waste. Particular attention was given to epoxy, polyurethane, and cyanoacrylate adhesives, as they are among the most widely used and effective bonding solutions in this field in textile materials, which may be subject to mechanical stress. Cyanoacrylate adhesives, due to their fast-curing speed and high tensile strength, are effective for quick repair and precise joints, however, their limited heat resistance and lower resistance to moisture limit their use in the production of materials subject to extreme operating conditions. Cyanoacrylate adhesives can be used to connect small parts where instant gripping and strength are required.

Polyurethane adhesives have proven to be the most versatile and suitable for use in the production of complex textile materials based on waste from the leather industry. They offer a high tensile strength of up to 30 MPa, which allows them to withstand substantial loads often experienced in textiles. Polyurethane adhesives have good adhesion to a

variety of materials, including leather and textiles, which makes them ideal for use in the manufacture of shoes, accessories, and furniture upholstery materials. Their high temperature resistance, even at 150°C and resistance to moisture further increase their attractiveness for various operating conditions.

This study confirmed that the choice of glue for the production of complex textile materials from processed leather fibres should be based on the specific requirements and operating conditions of the final products. It is important to carefully consider the operating conditions to choose the most suitable adhesive for a particular application, which will achieve maximum efficiency and durability of finished products. However, it should be noted that this study has its limitations since the examined set of types of adhesives was considered only in laboratory tests, which may differ from actual production conditions. For further research in the field, it is also recommended to expand the range of adhesive compositions under study, including new formulas and modifications with the introduction of various additives. In addition, it is important to deepen the consideration of the impact of operating conditions on the durability and quality of adhesive joints in real production conditions.

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Authors' Declarations and Essential Ethical Compliances

Author's Contributions (in accordance with ICMJE criteria for authorship)

This article is 100% contributed by the sole author. She conceived and designed the research or analysis, collected the data, contributed to data analysis & interpretation, wrote the article, performed critical revision of the article/paper, edited the article, and supervised and administered the field work.

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